CORP Science Symposium, July 18-19, 2016, Fort Collins

Development of High-Resolution Rapid Refresh (HRRR) Ensemble Data Assimilation, Forecast and Post-Processing

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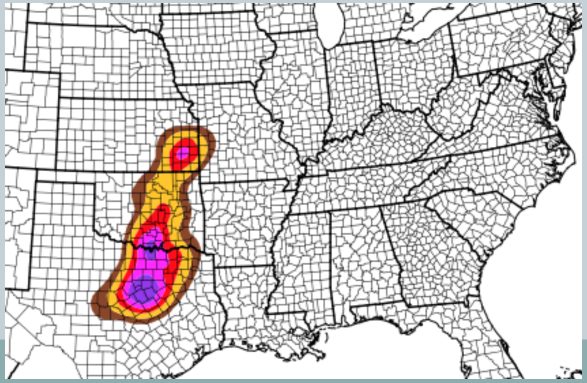
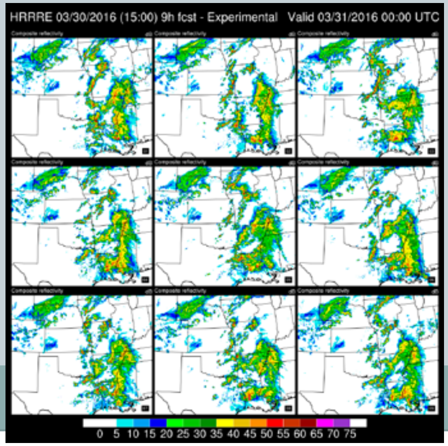
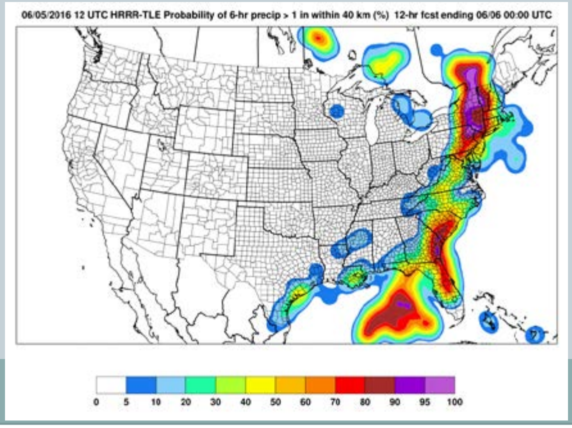






Outline

- RAP and HRRR models development including DA
- Shifting focus toward ensemble DA and forecasting
- Moving toward next generation of regional rapid-refresh storm-scale ensemble
- Starting points in DA
- Experiments in stochastic physics arena for the purposes of both DA and forecasting
- Statistical post-processing

RAP/HRRR: Hourly-Updating Weather Forecast Models

13-km Rapid Refresh (RAPv3) – to 21h (July 2016)

Expanded RAP to match NAM for SREF

(July 2016)

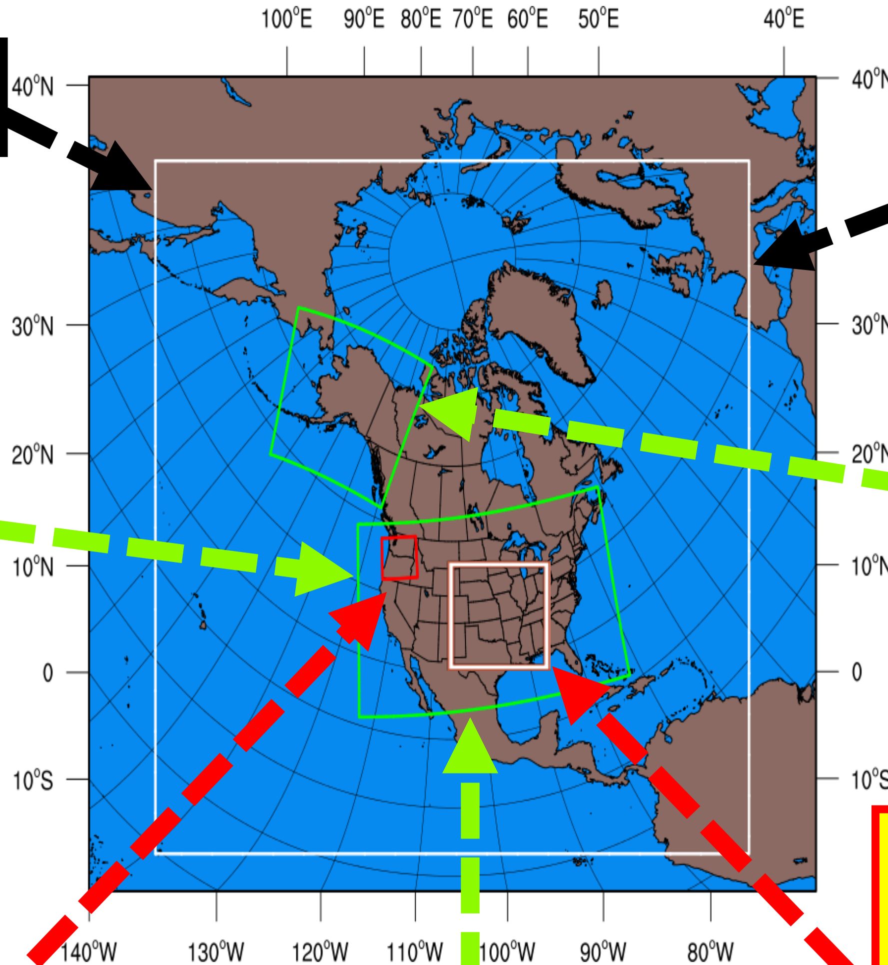
Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRRv2) – to 18h (July 2016)

3-km High-Resolution Rapid Refresh Alaska Testing (HRRR-AK) w/MRMS radar data

(Spring 2016)

Initial & Lateral Boundary Conditions



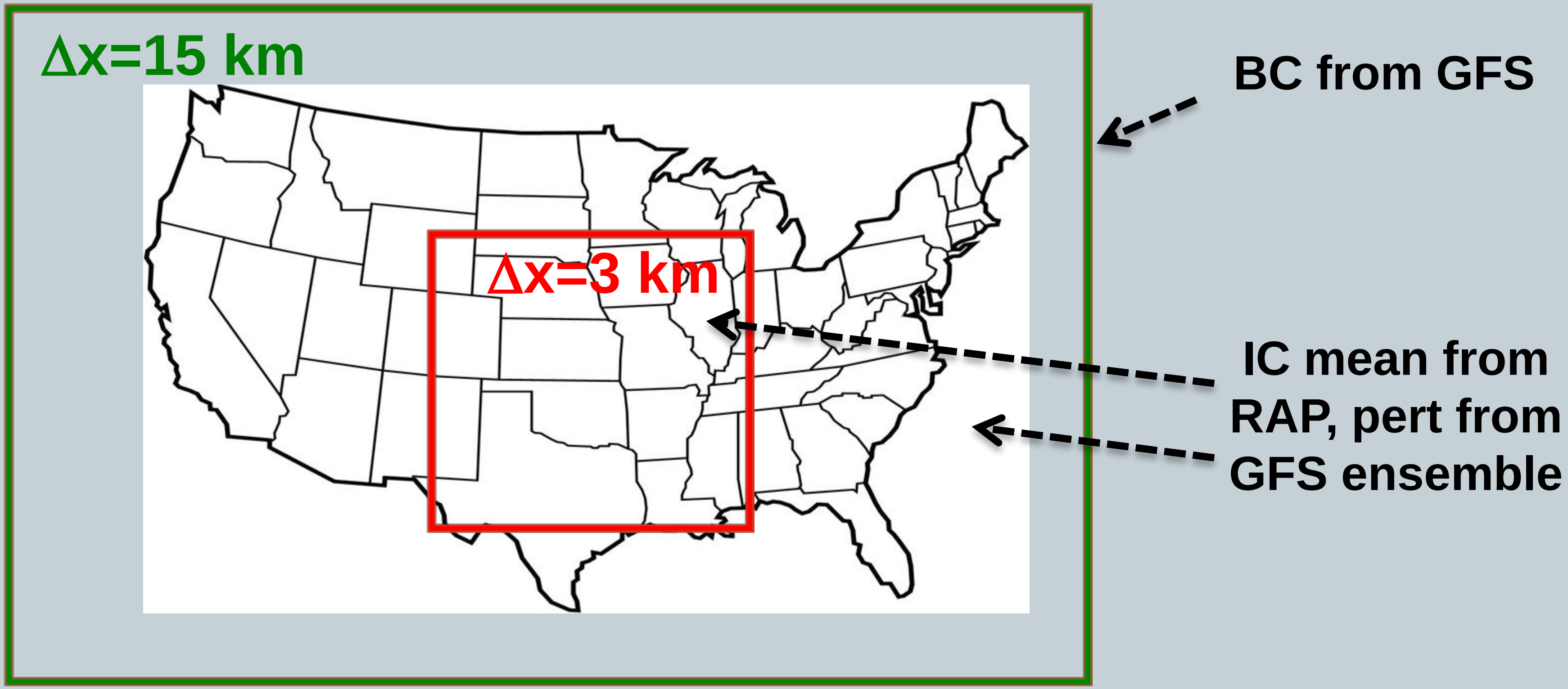
750-m HRRR nest Wind Forecast Improvement Project Experiment (ongoing)

3-km High-Resolution Time Lagged Ensemble (HRRR-TLE)

Prototype 3-km storm-scale HRRR ensemble (HRRRE)

(Spring 2016)

Spring 2016 Experimental HRRRE



Real-Time Web Graphics
http://rapidrefresh.noaa.gov/HRRRE

HRRRE Design

- **Community tools**
  - WRF for numerical weather prediction
  - GSI for observation processing and ensemble-prior calculation
  - EnKF for data assimilation

- **Hourly data assimilation** from 2100 UTC day 0 to 1800 UTC day 1
  - conventional observations only (radar reflectivity soon)
  - pure ensemble Kalman filter (EnKF)
    - variety of scales, including explicit convection, represented in background error covariances from 3-km ensemble
    - updated state variables: u, v, T, q_v, geopotential, column dry air mass
  - covariance localization: 500 km horizontal, 0.4 scale height

- **Ensemble 12+ h forecasts** at selected times
  - 18-member forecast at 1500 UTC provides initial and boundary conditions for NEWS-e

- **Sources of ensemble spread**
  - initial condition perturbations from GFS ensemble
  - model integration
  - adaptive, multiplicative posterior inflation

HRRRE Resources

HRRRE Real-Time System on NOAA R&D "Jet"
2 May - 20 June 2016 (testing in March/April)
HRRRE ~650x550 = 357,500 grdpts
HRRR 1800x1060 = 1,908,000 grdpts
HRRRE ~ 20% HRRR (1/5th)

Ensemble Pre-Processing

LBC	64 cores	~ 15 min
IC	120 cores	~ 30 min

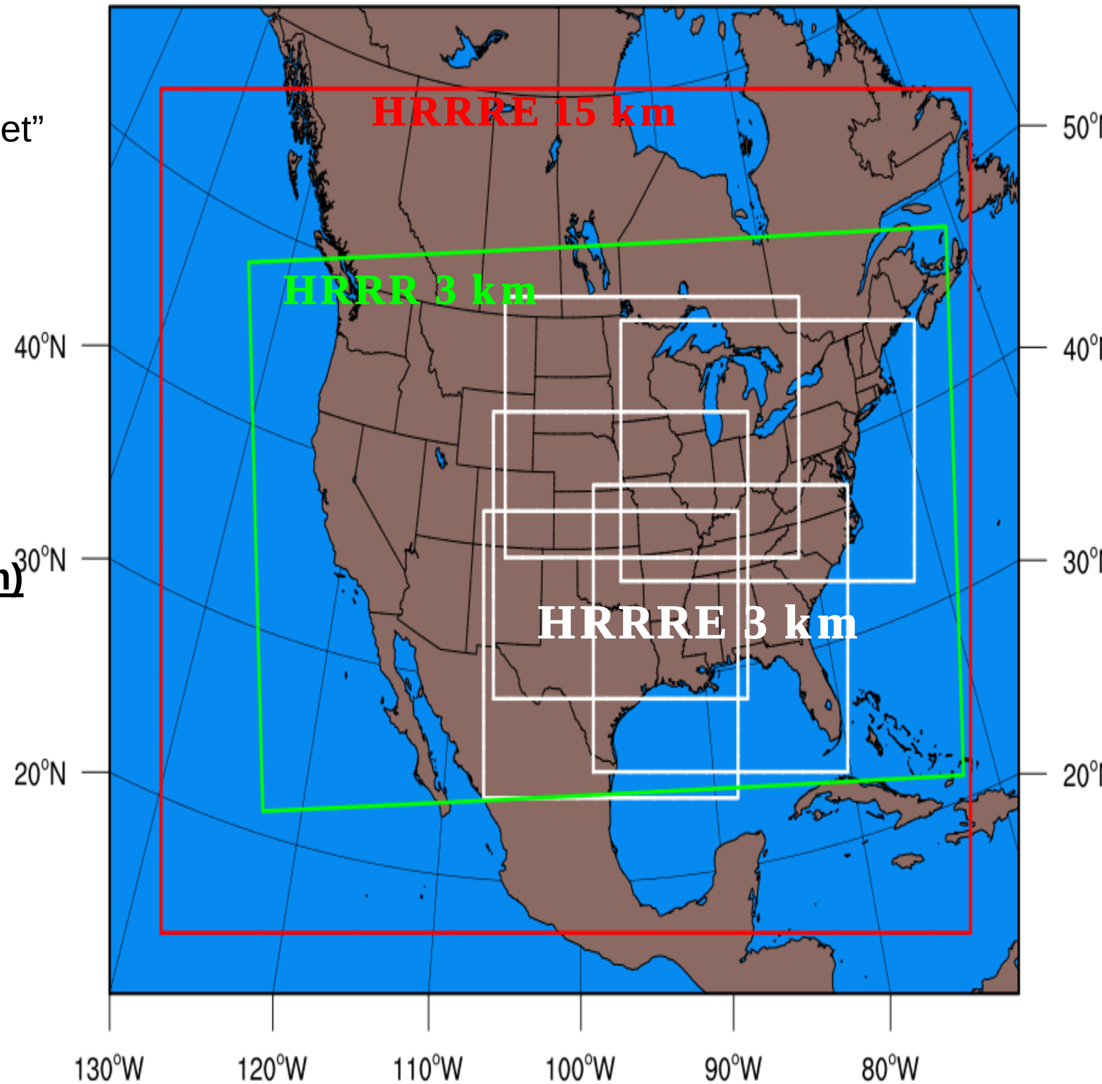
Ensemble 3-km Data Assimilation (20 mem)

WRF 1-hr cycle	72 cores/mem	~ 20 min
GSI-EnKF	240 cores	~ 25 min

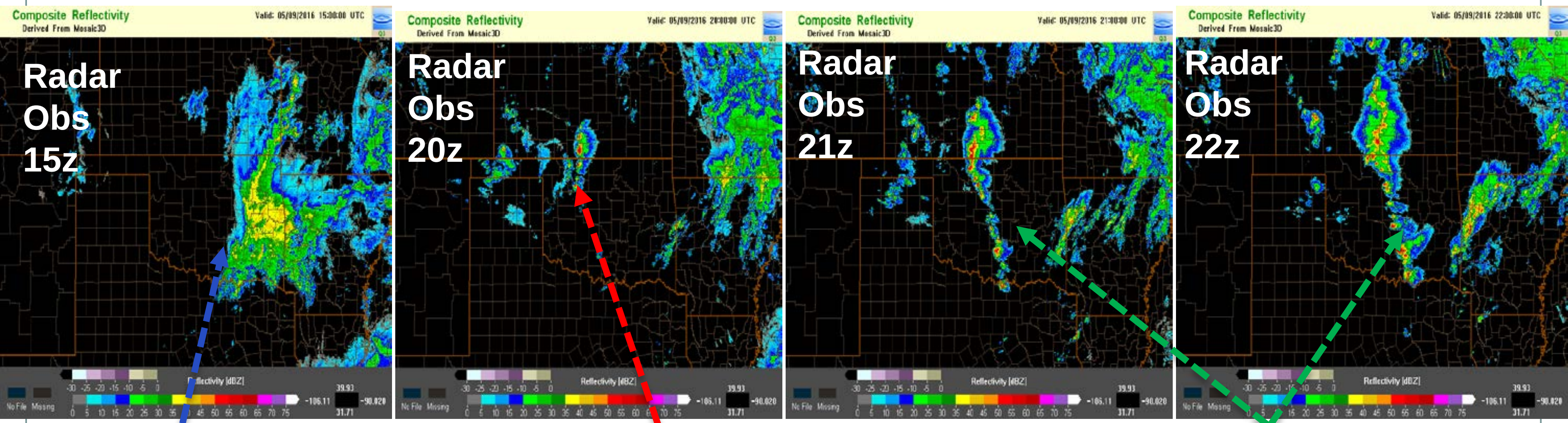
Ensemble 3-km Forecast (3-18 mem)

WRF 18-hr fcst	180 cores/mem	~120 min
Post-processing	16 cores/mem	~5 min

DA + FCST = ~5,000 cores (18 fcst mem)



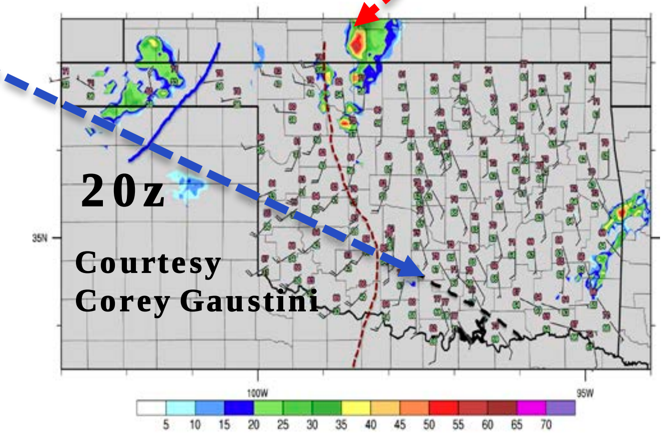
HRRRE: Case Study 09 May 2016

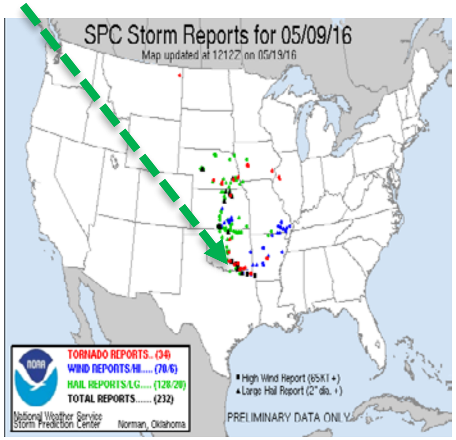


Rain-cooled Boundary

Convective initiation along dryline

Tornadic supercell development near residual outflow boundary intersection





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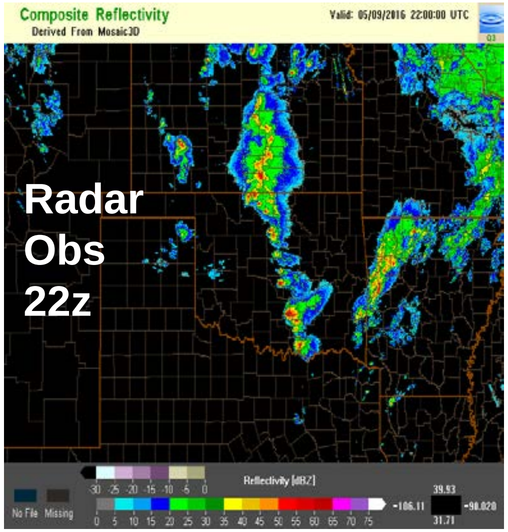
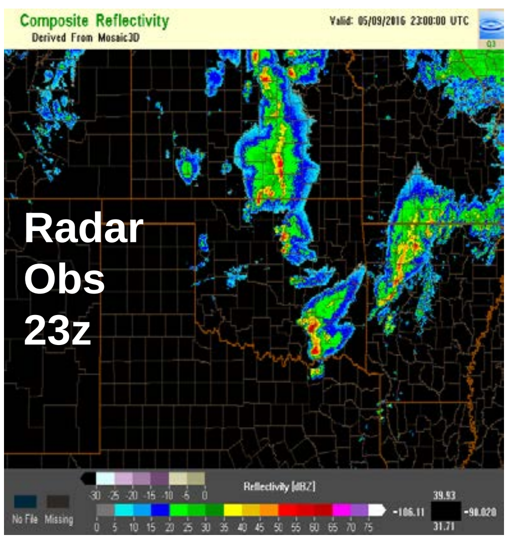
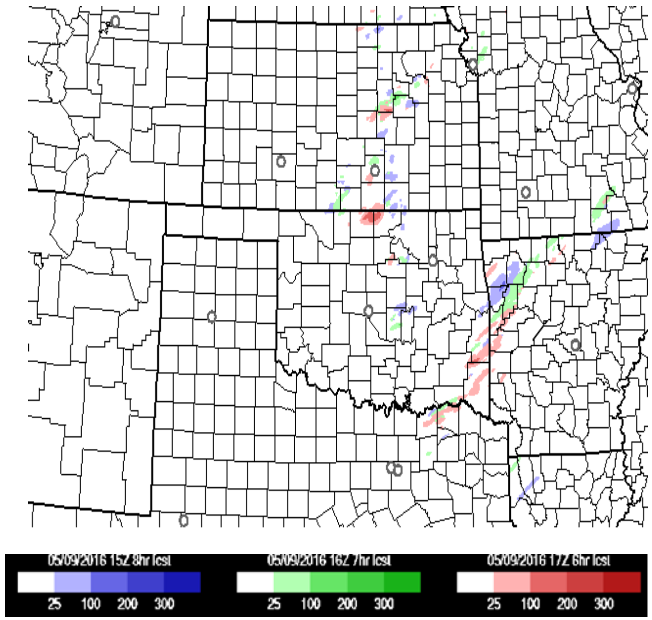


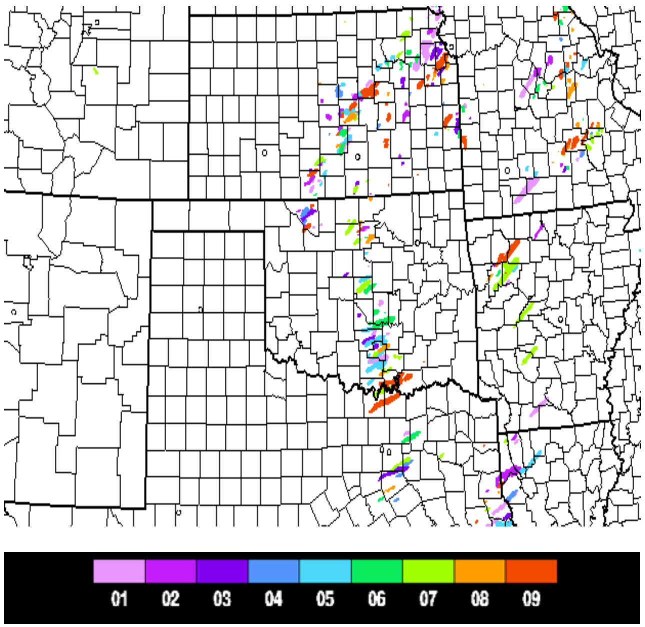


1-hr Maximum Updraft Helicity Valid 22z (colors > 25 m^2/s^2)

HRRRX 15z-17z initializations
Time-Lagged Ensemble



HRRRE 15z + 7hr fcst valid 22z



Effective use of the boundary observations in storm-scale ensemble data assimilation

HRRRE Observation Space Diagnostics: 1-hr cycling

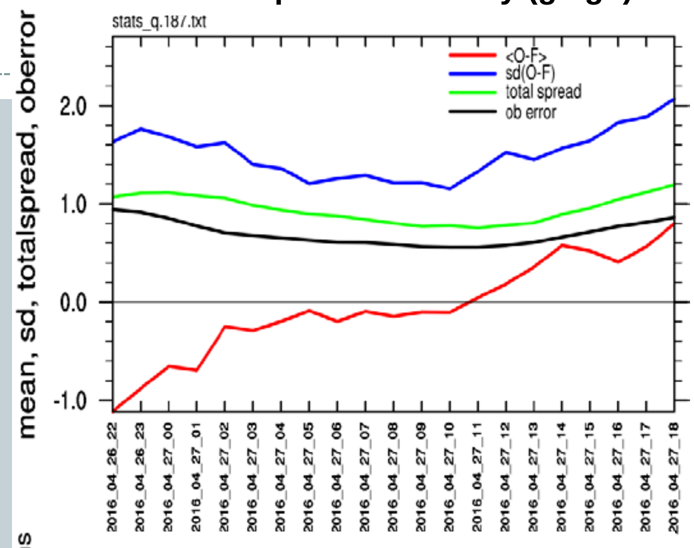
Black = Observation Error
Red = Ens Bias (mean obs innovation)
Green = Total Spread (ensemble standard deviation + ob error)
Blue = Ens Forecast Error (innovation standard deviation)

Need accurate specification of observation error
Ensemble spread << Observation error → Not drawn towards obs in DA
Based on results observation errors reduced for some datasets

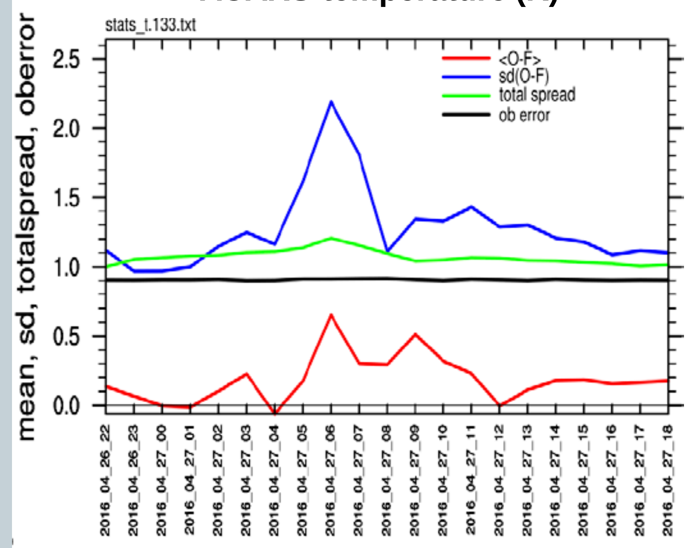
Want total spread to track with forecast errors of the day
Ensemble spread < Forecast error (green < blue) → Underdispersive
Ensemble spread > Forecast error (green > blue) → Overdispersive
Ensemble generally underdispersive

Ensemble design refinements planned including… statistical post-processing

METAR specific humidity (g kg^{-1})



ACARS temperature (K)



Stochastic physics for use in Regional/Storm Scales Ensembles

Motivation

- Issues with mixed-physics approach
  - Maintenance
  - Inconsistent ensemble system (some schemes closer related than others)
  - Each member has a unique climatology and mean error
- Compare mixed-physics approach to stochastic parameter perturbation (SPP), Stochastic Kinetic Energy Backscatter (SKEB) and Stochastic Perturbation of Physics Tendencies (SPPT).

Experiment Design

- Regional RAP model simulations
- 7 days from 2013 convective season: May 23,29; June 7, 14, 20, 28; July 4
- 24 h forecasts
- 00 and12 Z initializations using different GEFS members
- Stochastic Parameter Perturbation, SKEB and SPPT
- Focus on convective Grell-Freitas and MYNN PBL
- Verification performed over CONUS
- Statistical significance testing by employing boot strap method with 95% confidence interval

Experiments

CU comparison

Control mixed physics

(CU and PBL)

SPP

(CU and PBL)

PBL comparison

SPP+SKEB

(CU + PBL)

SPP+SPPT

(CU+PBL)

SPP+SKEB+SPPT

(CU+PBL)

Impact of adding SKEB and SPPT on stochastic parameter perturbation

Mixed-physics and stochastic members

Mixed-physics members	Convective	PBL	LSM
control0	OSAS	MYNN	RUC
contol1	BMJ	MYNN	RUC
control2	GF	MYNN	RUC
control3	NSAS	MYNN	RUC
control4	GF	MYJ	RUC
control5	GF	YSU	RUC
control6	GF	BOULAC	RUC
control7	GF	MYNN	RUC

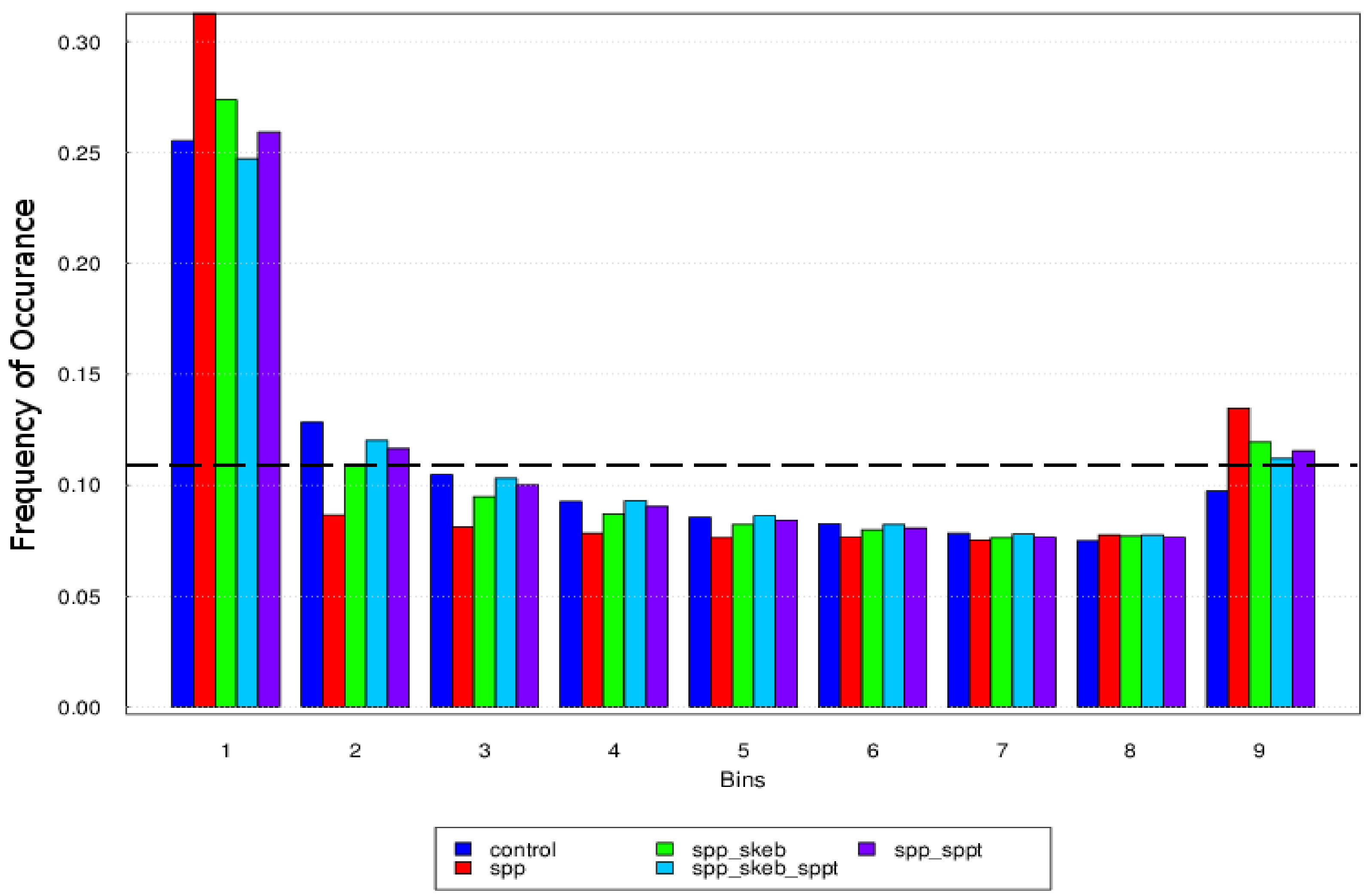
Stochastic	Convective	PBL	LSM
stoch0	GF-pert	MYNN	RUC
stoch1	GF-pert	MYNN	RUC
stoch2	GF-pert	MYNN	RUC
stoch3	GF-pert	MYNN	RUC
stoch4	GF	MYNN-p	RUC
stoch5	GF	MYNN-p	RUC
stoch6	GF	MYNN-p	RUC
stoch7	GF	MYNN-p	RUC

Perturbed parameters

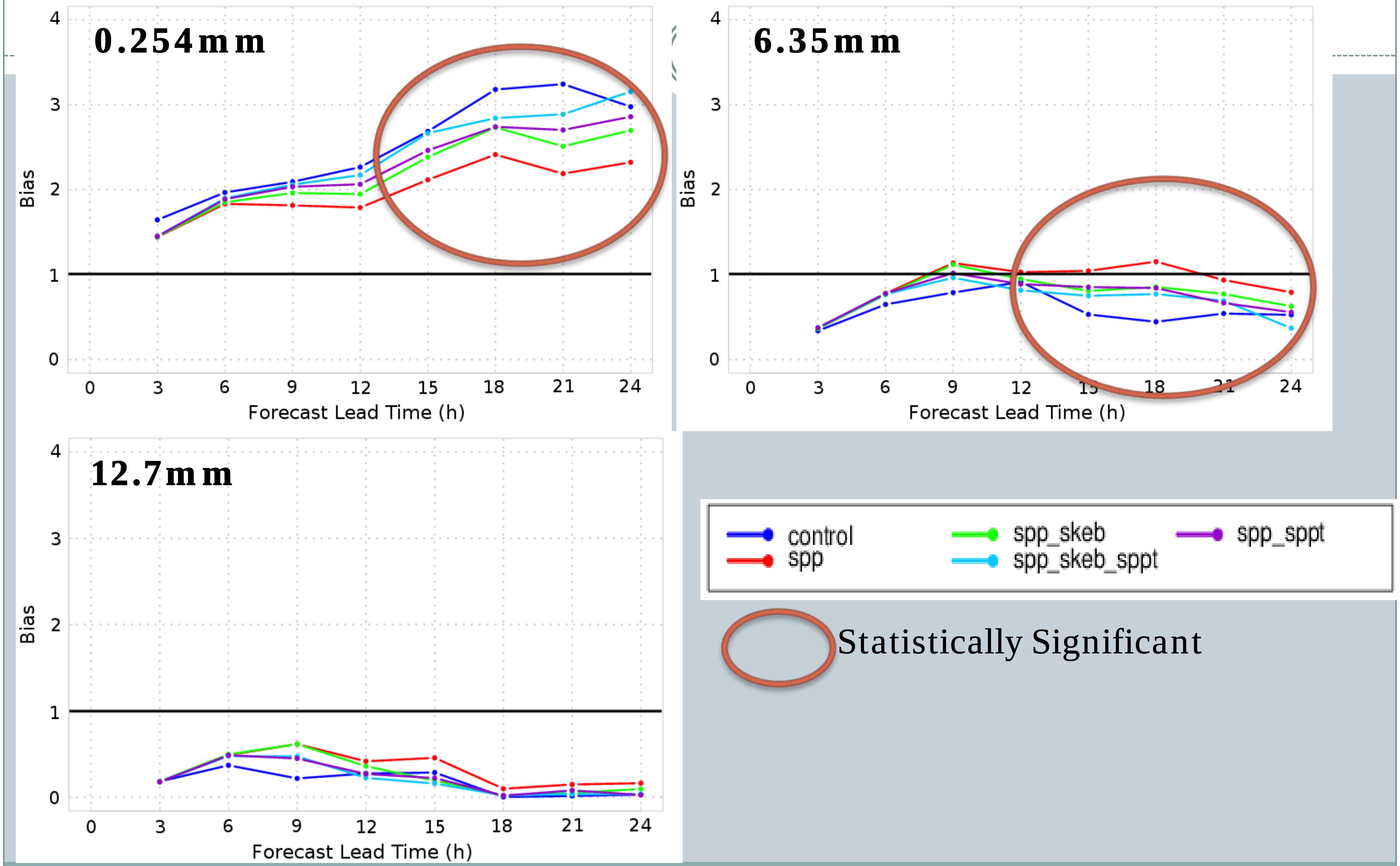
GF CU scheme: Closures

MYNN PBL: Turbulent mixing length
Sub-grid cloud fraction
Roughness length (T & moist.)

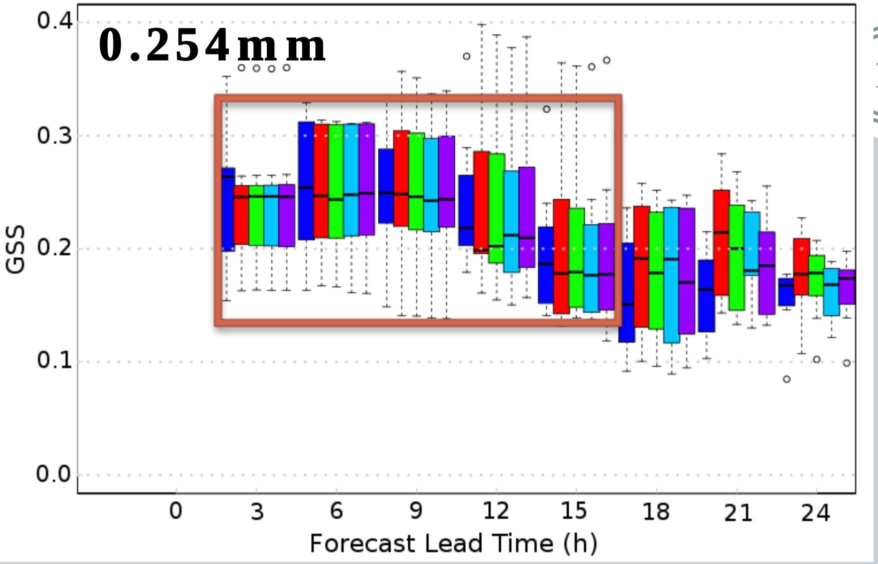
Precipitation Rank histograms for 00 Z initialization:

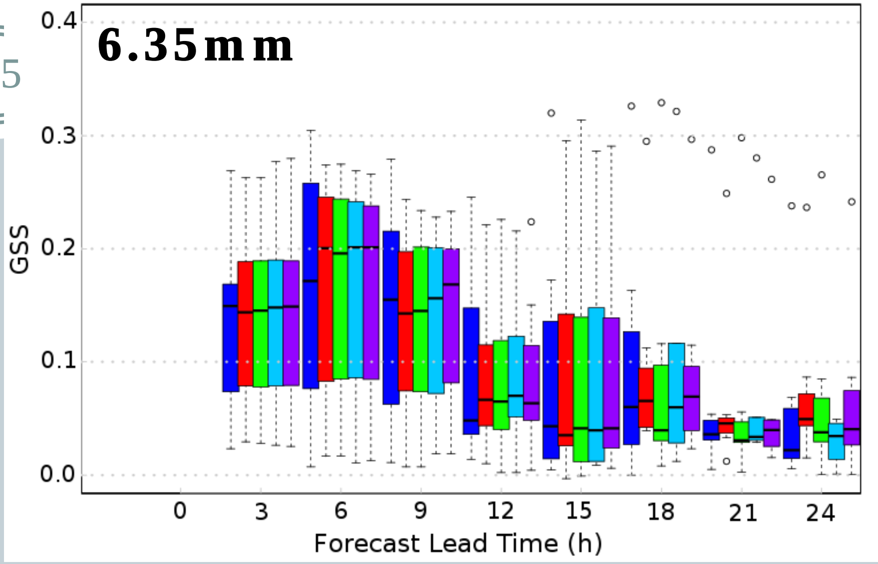


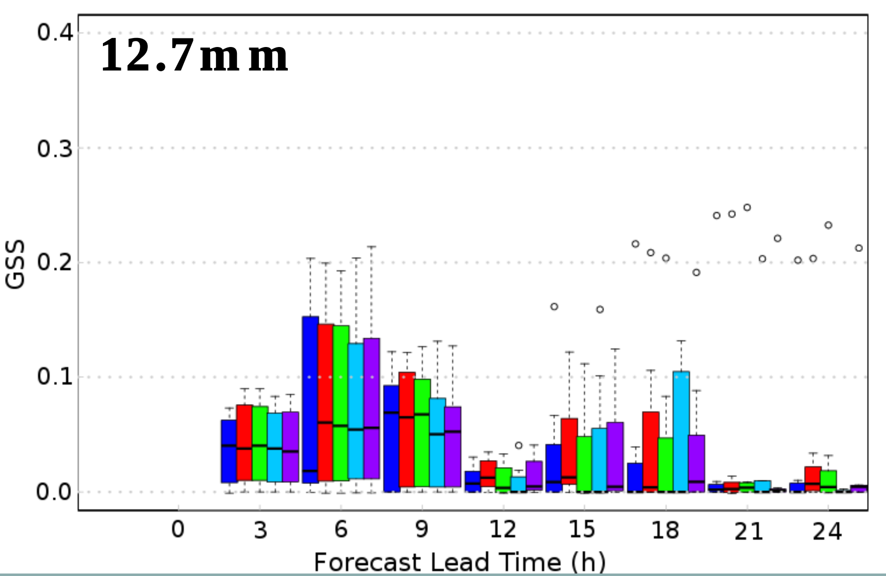
Ensemble Mean Bias – 00Z init.

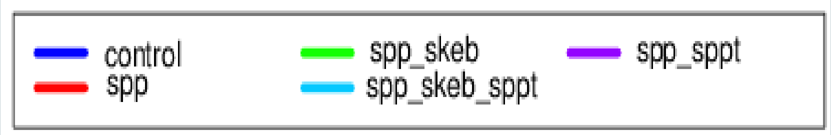


Ensemble Mean GSS – 00Z Init.

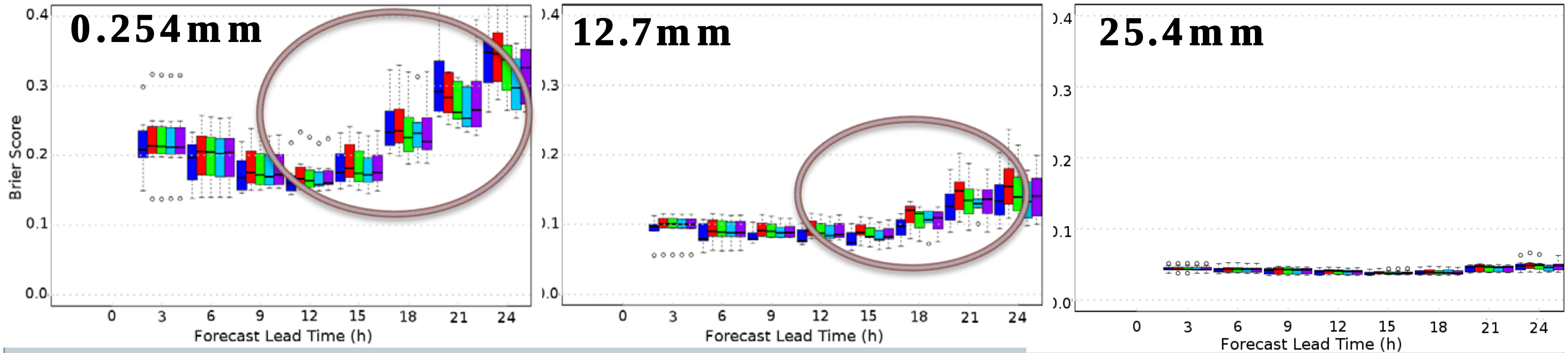




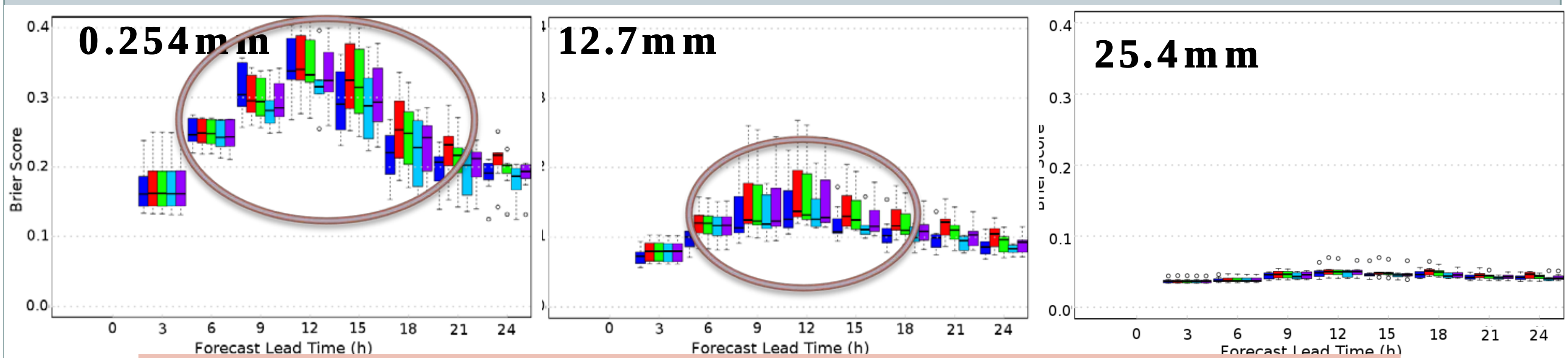




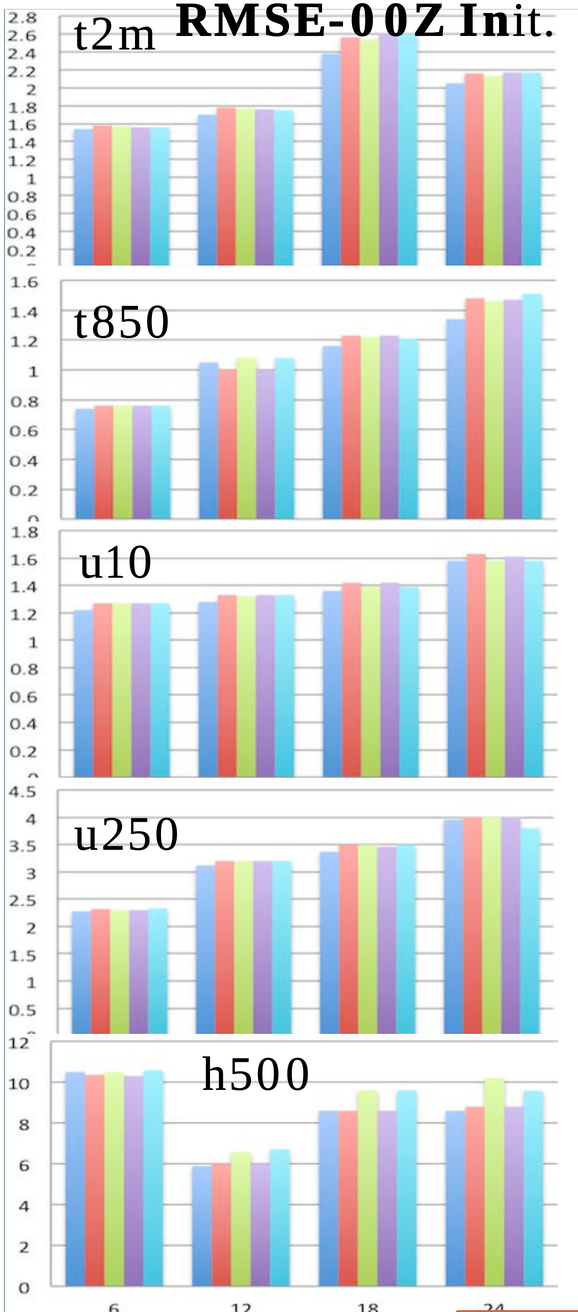
Brier Score - 00 Z initialization



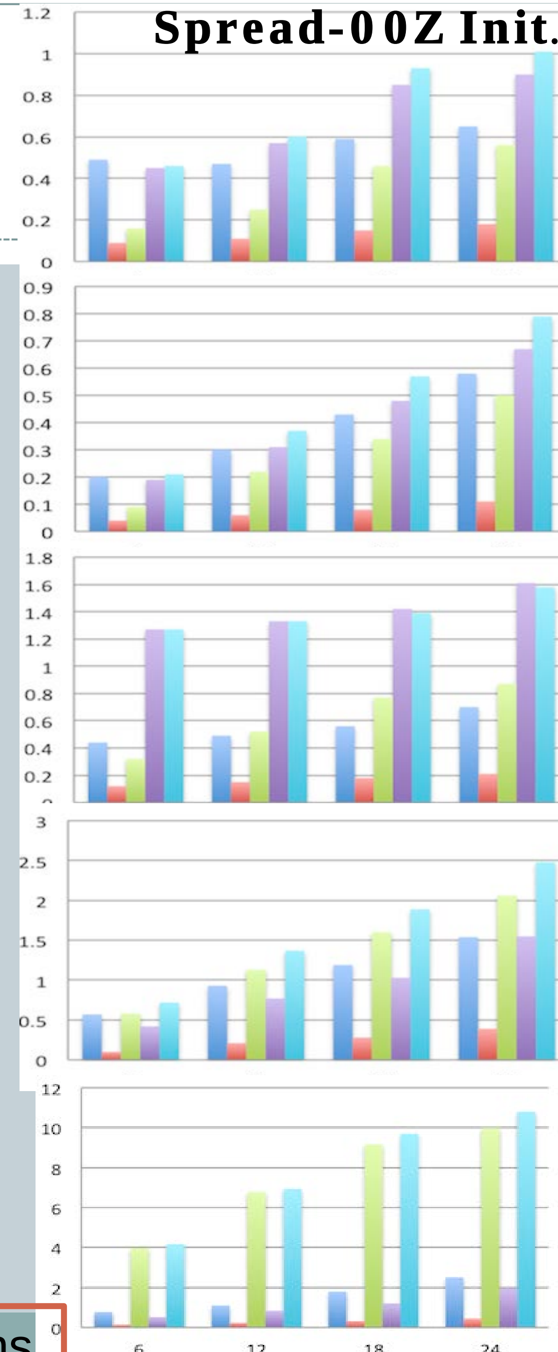
Brier Score - 12 Z initialization



During the day stochastic experiments significantly outperform the control.
spp_skeb_sppt significantly better than others.
Situation opposite **during the night**.



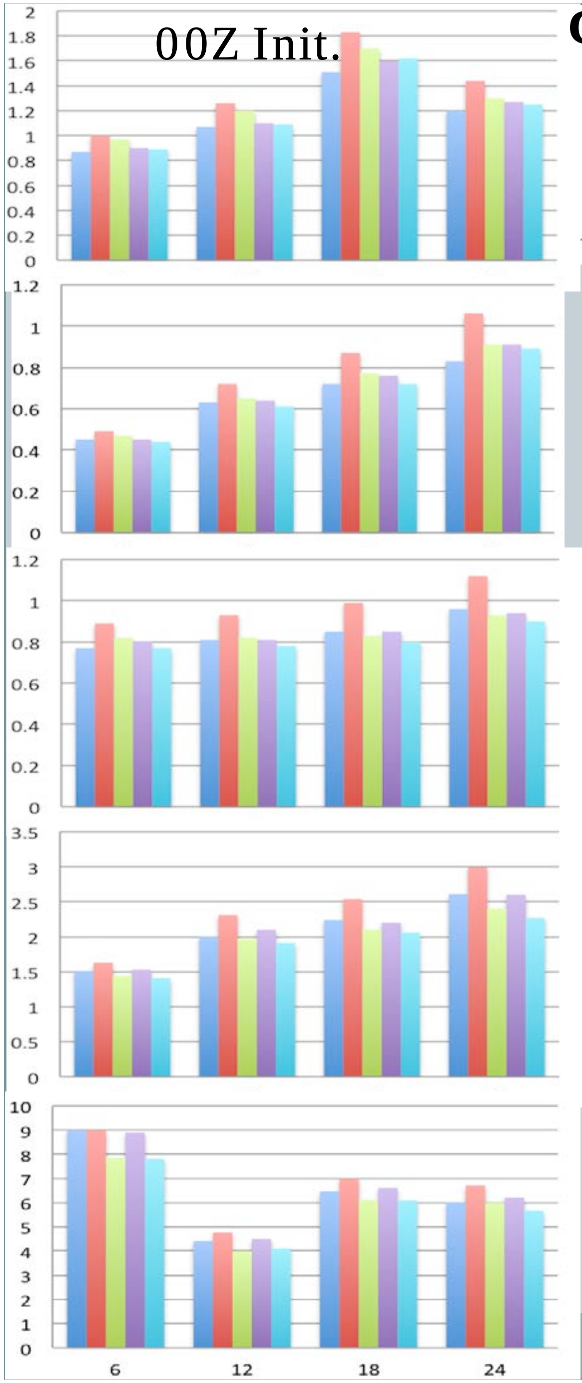
spp_skeb_sppt spread significantly higher when compared to the control experiment, for most of the lead times (longer than 6hrs) and all variables.



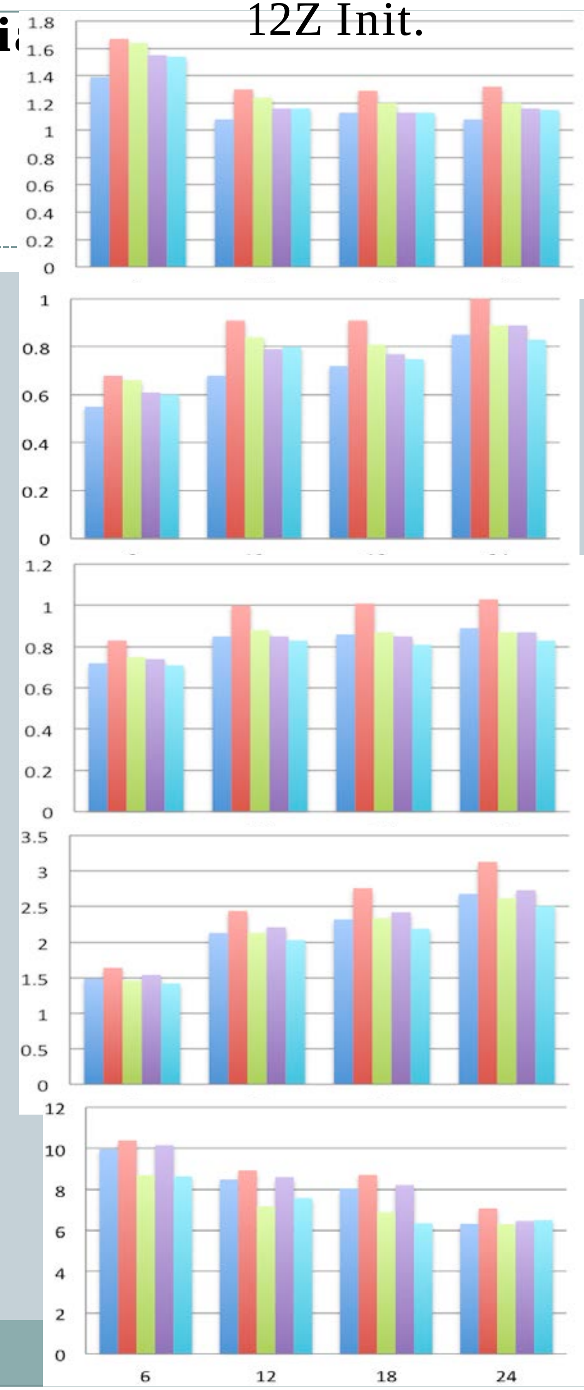
Very similar results for 12Z simulations

CRPS for 00Z and 12Z Initi

00Z Init.



12Z Init.



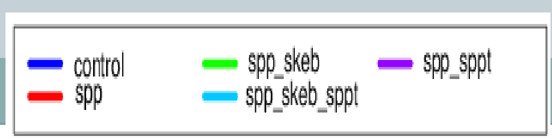
t2m

t850

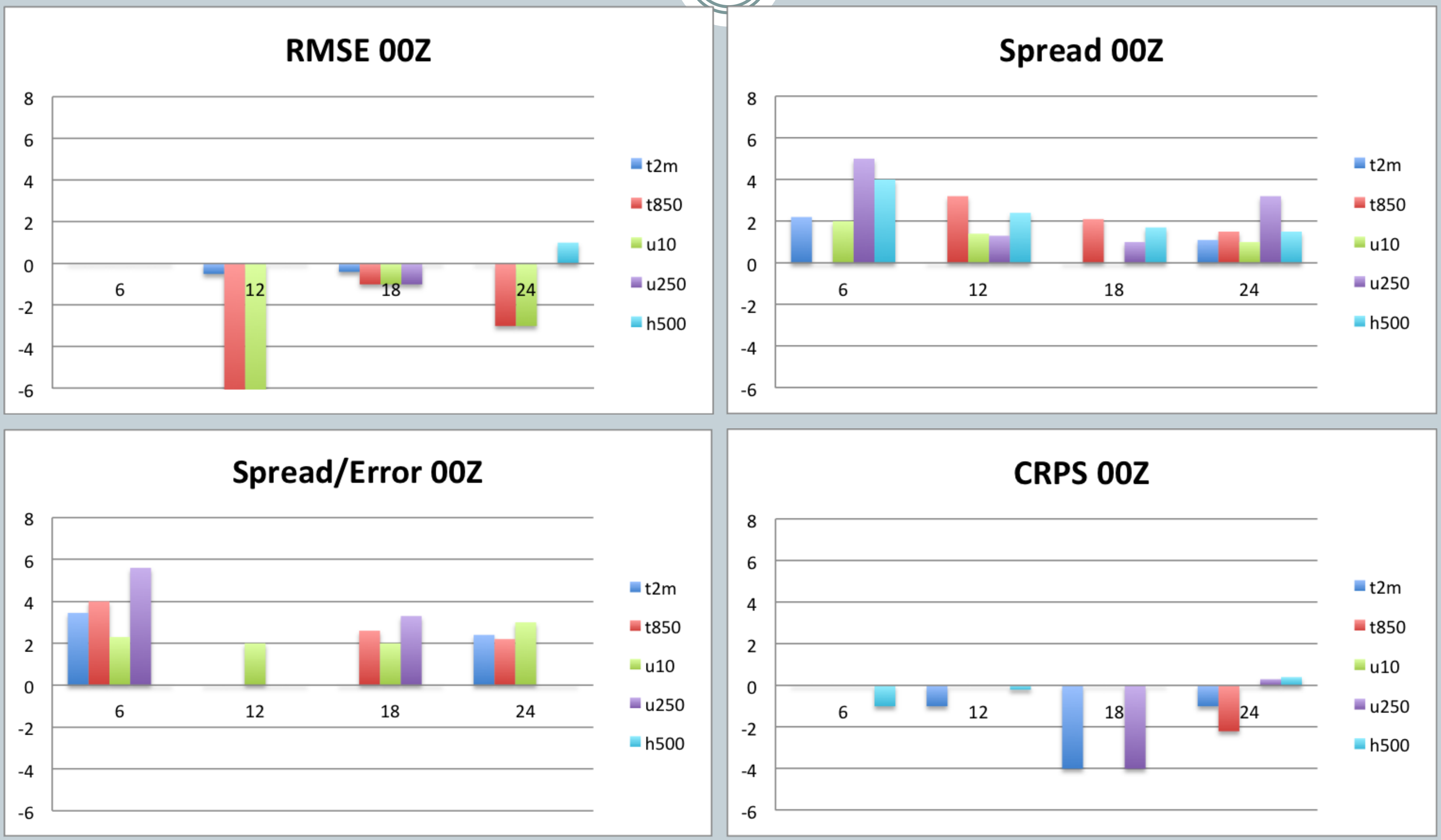
u10

u250

h500



SPP+SPPT – SPPT experiments



Stochastic Physics Tests Summary

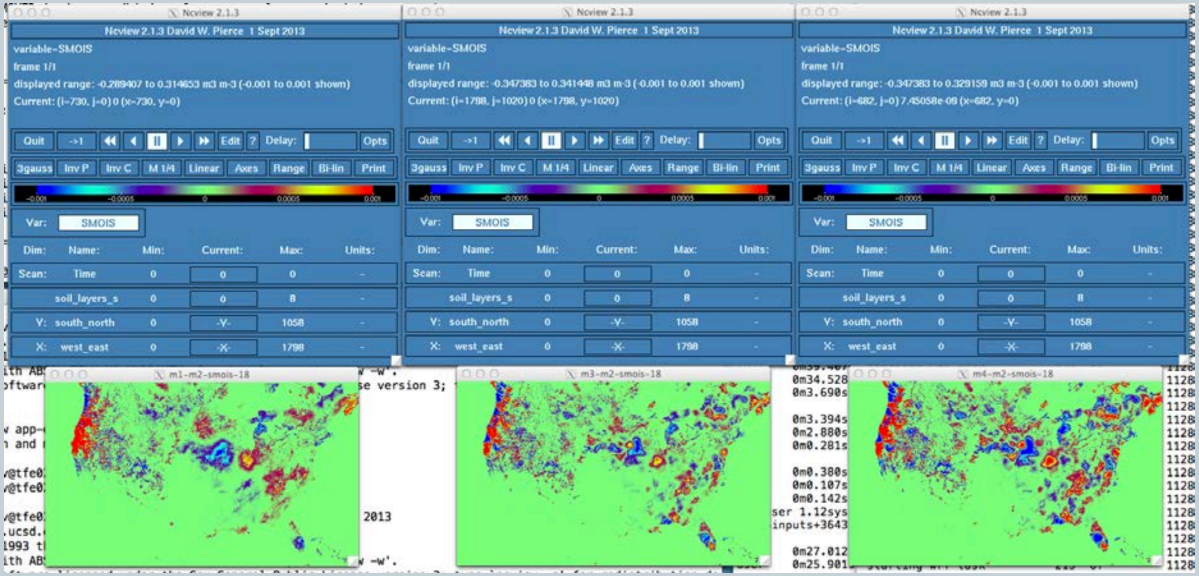
- Alone, the parameter perturbations of SPP introduce insufficient spread.
- When combined with SKEB and/or SPPT the spread is as large and for some instances even larger than for a multi-physics ensemble.
- An ensemble created by combining three stochastic approaches (SPP, SKEB and SPPT generally outperformed the multi-physics, control ensemble for most of the examined variables, most of the evaluated lead times, and most of the employed statistics.
- SKEB made a larger impact on spread associated with upper level wind and geopotential heights, while SPPT had a larger impact on spread for near-surface temperature.
- Combining SPP with SPPT has generally a positive impact, on the order of a 2-10% improvement over an ensemble using SPPT alone.

1. The results confirm the findings of previous studies that parameter perturbations alone do not generate sufficient spread to remedy the under-dispersion in short-term ensemble forecasts

2. A combination of several stochastic schemes outperforms any single scheme. This result implies that a synthesis of different approaches is best suited to capture model error in its full complexity.

Current and Future Work

- Adding 14 more cases to the previous study
- Experimenting with HRRR (3km grid spacing) for application in HREF
- Focus on PBL and LSM:
  - PBL-In addition to mixing length, roughness length and cloud fraction we added perturbations to mass fluxes
  - LSM-Hydraulic Conductivity is currently being perturbed



HRRR Time-Lagged Ensemble (HRRR-TLE)

Deterministic HRRR:

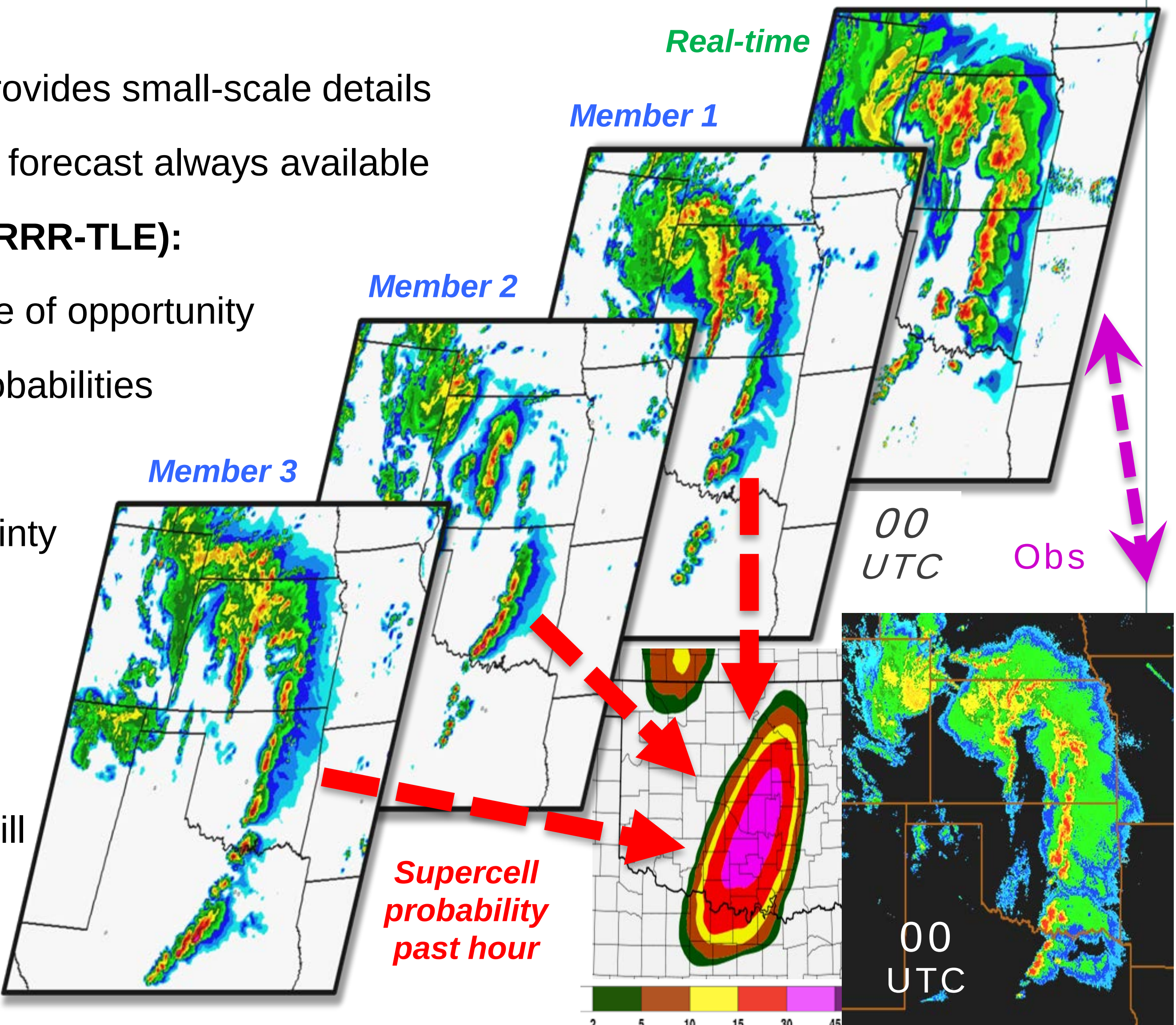
- High-resolution forecast provides small-scale details
- Hourly-updating with fresh forecast always available

Time-Lagged Ensemble (HRRR-TLE):

- Leverage runs in ensemble of opportunity
- Form hazard likelihood probabilities
- Less small-scale detail
- Proxy for confidence/certainty
- Underdispersive

HRRR Ensemble (HRRRE):

- More expensive ensemble
- More spread/dispersive/skill



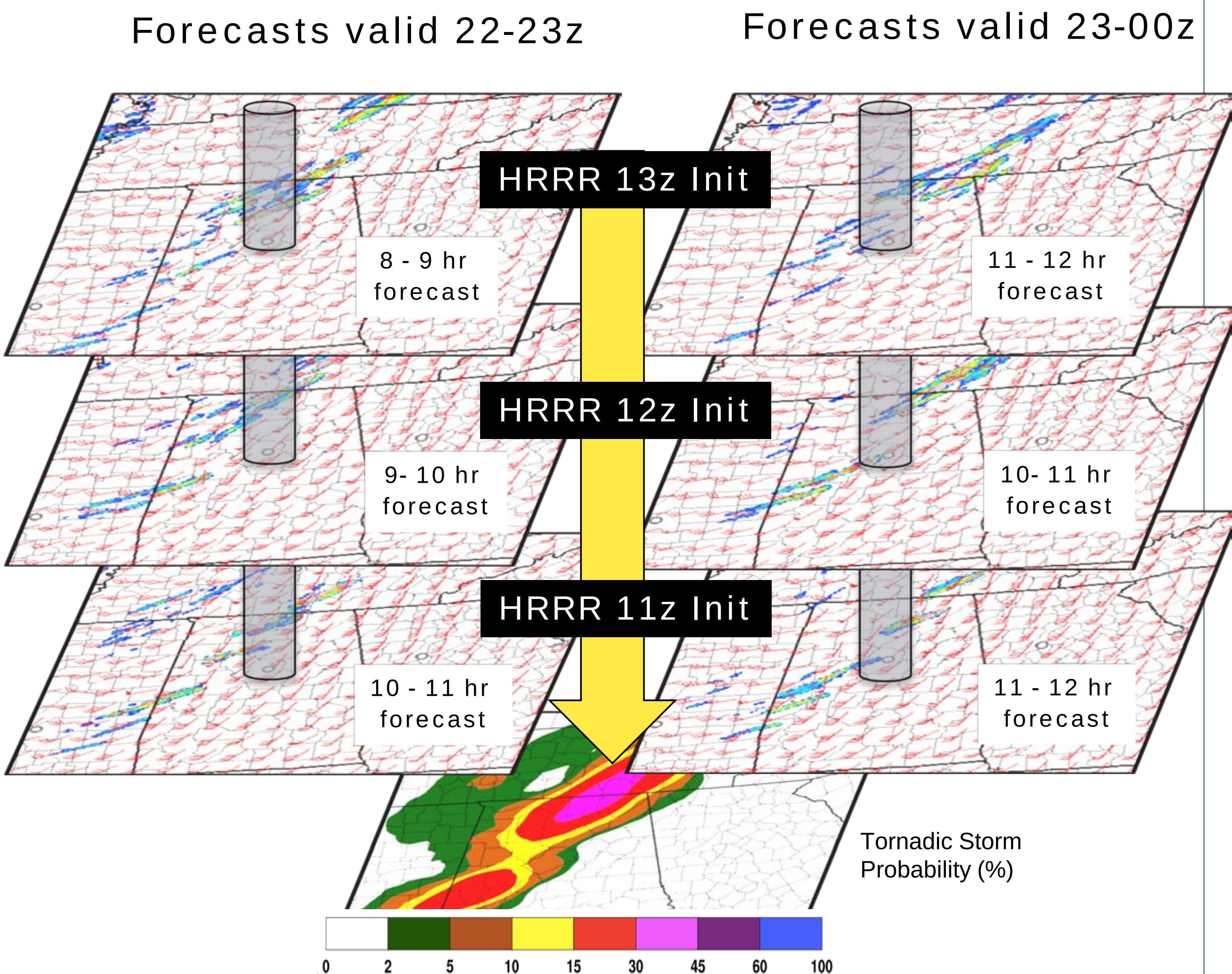
HRRR-TLE Severe Weather Example

Neighborhood Search

Point Probability

Spatial radius 45 km
Time radius 1 hr
UH threshold 25 m^2/s^2

All six forecasts combined to form probabilities valid 22z 27 April 2011



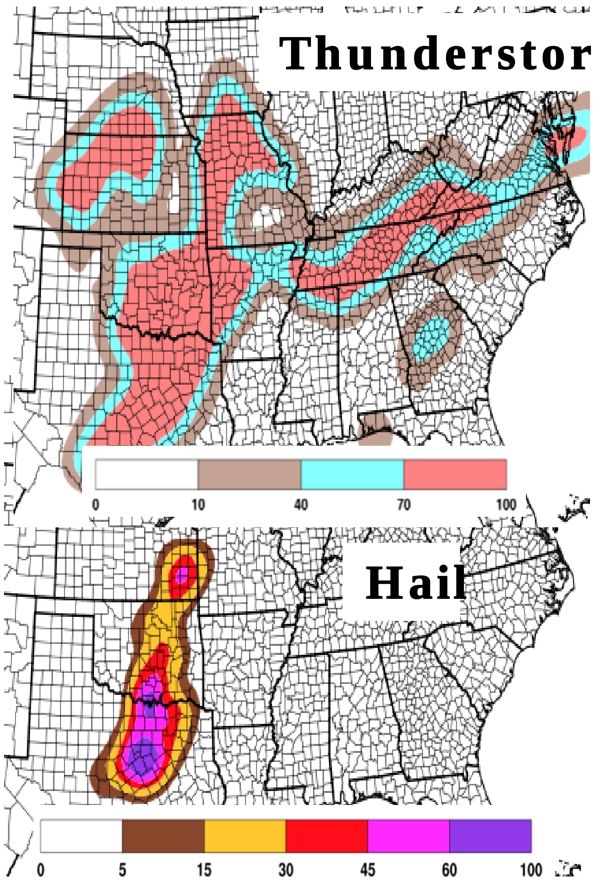
HRRR Time-Lagged Ensemble (HRRR-TLE)

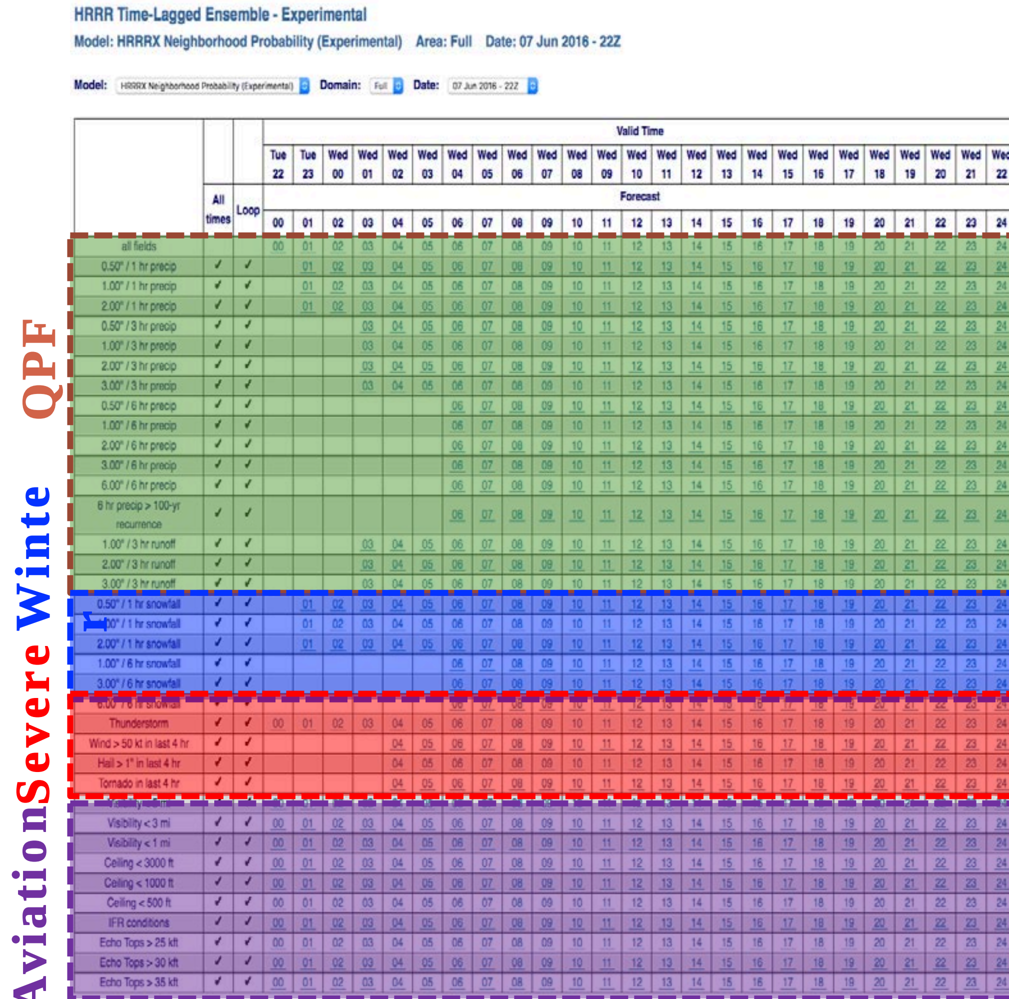
Current Experimental Probability Products:

- Based on 3 HRRRX runs (equal weight)
- Starting with forecast hour two
- 40-km neighborhood probabilities
- 120-km spatial filter applied *after* identifying neighborhood hazard exceedance

Real-Time Web Graphics (and grids via LDM/FTP)

http://rapidrefresh.noaa.gov/hrrrtle





HRRR Time-Lagged Ensemble - Experimental

Model: HRRRX Neighborhood Probability (Experimental) Area: Full Date: 07 Jun 2016 - 22Z

Model: HRRRX Neighborhood Probability (Experimental) Domain: Full Date: 07 Jun 2016 - 22Z

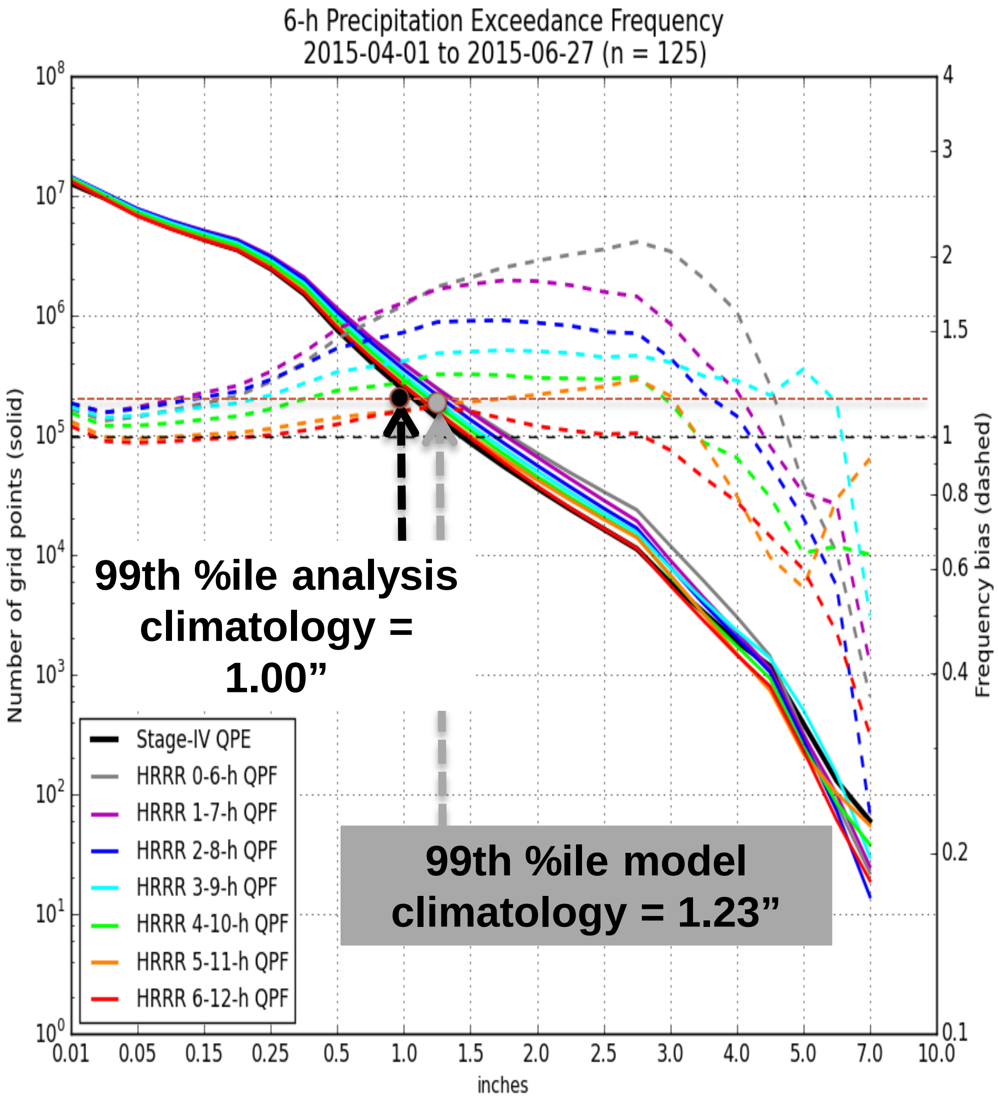
			Valid Time																							
			Tue 22	Tue 23	Wed 00	Wed 01	Wed 02	Wed 03	Wed 04	Wed 05	Wed 06	Wed 07	Wed 08	Wed 09	Wed 10	Wed 11	Wed 12	Wed 13	Wed 14	Wed 15	Wed 16	Wed 17	Wed 18	Wed 19	Wed 20	Wed 21	Wed 22
	All times	Loop	Forecast																								
			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
all fields			00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.50" / 1 hr precip	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.00" / 1 hr precip	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2.00" / 1 hr precip	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.50" / 3 hr precip	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.00" / 3 hr precip	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2.00" / 3 hr precip	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3.00" / 3 hr precip	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.50" / 6 hr precip	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.00" / 6 hr precip	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2.00" / 6 hr precip	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3.00" / 6 hr precip	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
6.00" / 6 hr precip	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
6 hr precip > 100-yr recurrence	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.00" / 3 hr runoff	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2.00" / 3 hr runoff	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3.00" / 3 hr runoff	✓	✓				03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.50" / 1 hr snowfall	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.00" / 1 hr snowfall	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2.00" / 1 hr snowfall	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1.00" / 6 hr snowfall	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3.00" / 6 hr snowfall	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
6.00" / 6 hr snowfall	✓	✓							06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Thunderstorm	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Wind > 50 kt in last 4 hr	✓	✓					04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Hail > 1" in last 4 hr	✓	✓					04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Tornado in last 4 hr	✓	✓					04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Visibility [illegible]	✓	✓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Visibility < 3 mi	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Visibility < 1 mi	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Ceiling < 3000 ft	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Ceiling < 1000 ft	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Ceiling < 500 ft	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
IFR conditions	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Echo Tops > 25 kft	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Echo Tops > 30 kft	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Echo Tops > 35 kft	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

HRRR-TLE Development: Bias Correction

Frequency Bias Correction Using "Quantile Mapping"

Model forecast climatology adjusted to observation climatology for a particular threshold (1 inch / 6 hrs)

Exploring modified gamma distribution for additional refinement in bias correction



HRRR-TLE Precipitation Products

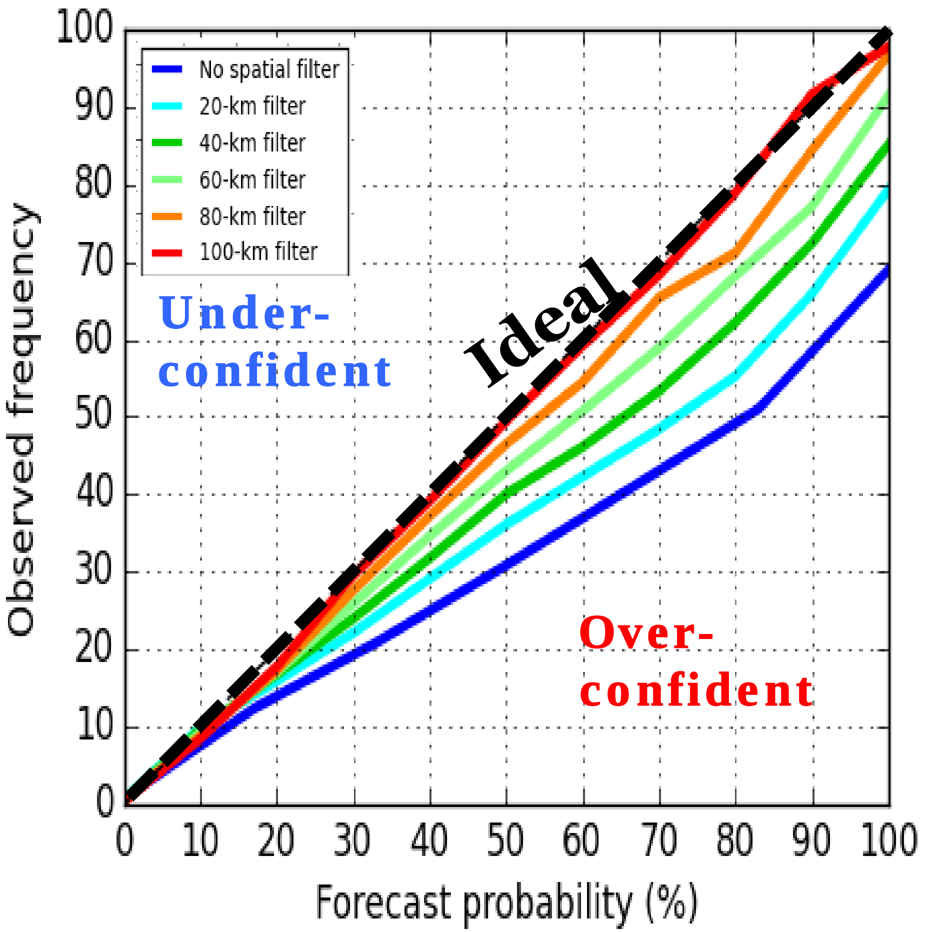
Results: Probability of 0.5” Precipitation in 6 hours May-Aug 2015

With relatively small sample size (~50 forecasts)

Produce statistically reliable probabilities 60% forecasts observed 60% of the time

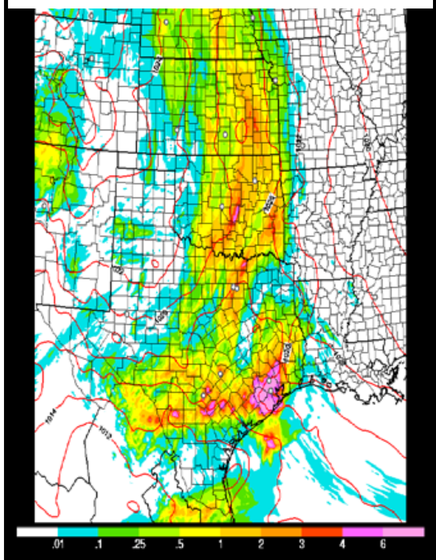
Produce probabilities with sufficient resolution/sharpness
Large dynamic range to probabilities including extremes

Still fundamentally underdispersive (overconfident)

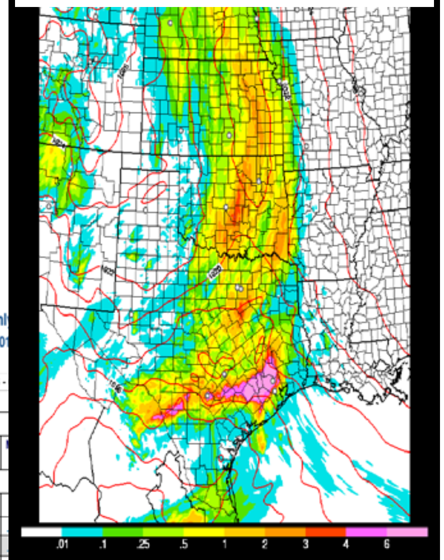


HRRR-TLE Case Study: 18 April 2016

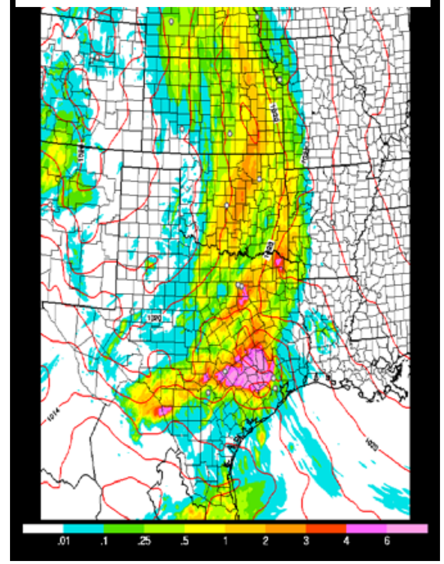
HRRR 23z 13hr pcp fcst

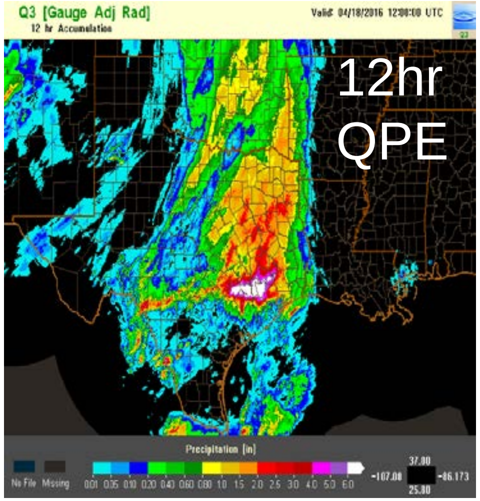


HRRR 00z 12 hr pcp fcst

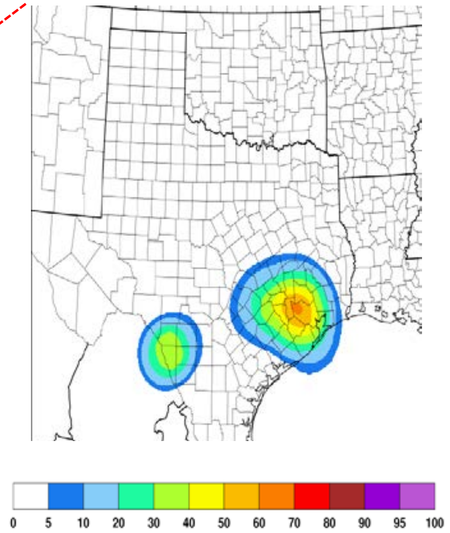


HRRR 01z 11 hr pcp fcst





2.00" / 1 hr precip	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	2.00" / 1 hr precip
0.50" / 3 hr precip	✓	✓				03			06			09			12	0.50" / 3 hr precip
1.00" / 3 hr precip	✓	✓				03			06			09			12	1.00" / 3 hr precip
2.00" / 3 hr precip	✓	✓				03			06			09			12	2.00" / 3 hr precip
3.00" / 3 hr precip	✓	✓				03			06			09			12	3.00" / 3 hr precip
0.50" / 6 hr precip	✓	✓							06			09			12	0.50" / 6 hr precip
1.00" / 6 hr precip	✓	✓							06			09			12	1.00" / 6 hr precip
2.00" / 6 hr precip	✓	✓							06			09			12	2.00" / 6 hr precip
3.00" / 6 hr precip	✓	✓							06			09			12	3.00" / 6 hr precip
6.00" / 6 hr precip	✓	✓							06			09			12	6.00" / 6 hr precip
6 hr precip > 100-yr recurrence	✓	✓							06			09			12	6 hr precip > 100-yr recurrence
1.00" / 3 hr runoff	✓	✓				03			06			09			12	1.00" / 3 hr runoff
2.00" / 3 hr runoff	✓	✓				03			06			09			12	2.00" / 3 hr runoff
3.00" / 3 hr runoff	✓	✓				03			06			09			12	3.00" / 3 hr runoff
0.50" / 1 hr snowfall	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	0.50" / 1 hr snowfall
1.00" / 1 hr snowfall	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	1.00" / 1 hr snowfall
2.00" / 1 hr snowfall	✓	✓		01	02	03	04	05	06	07	08	09	10	11	12	2.00" / 1 hr snowfall
1.00" / 6 hr snowfall	✓	✓							06			09			12	1.00" / 6 hr snowfall
3.00" / 6 hr snowfall	✓	✓							06			09			12	3.00" / 6 hr snowfall
6.00" / 6 hr snowfall	✓	✓							06			09			12	6.00" / 6 hr snowfall
Thunderstorm	✓	✓	00	01	02	03	04	05	06	07	08	09	10	11	12	Thunderstorm
Wind > 50 kt in last 4 hr	✓	✓					04	05	06	07	08	09	10	11	12	Wind > 50 kt in last 4 hr
Hail > 1" in last 4 hr	✓	✓					04	05	06	07	08	09	10	11	12	Hail > 1" in last 4 hr
Tornado in last 4 hr	✓	✓					04	05	06	07	08	09	10	11	12	Tornado in last 4 hr



HRRR-TLE forecasts > 60% probability of 6hr QPF exceeding 100 year average return interval (ARI) in Houston,TX area based on ATLAS14

HRRR-TLE: Product Development

Product Development Methodology

Hazard	**Proxy**	**Truth**
Heavy rainfall	QPF	Stage-IV / MRMS
Snowfall rate	Microphysics-based	ASOS visibility
Precipitation type	Microphysics-based	ASOS type
Accumulating snow	Explicit snow depth	Point observations
Severe wind	80-m hourly max wind or 10-m gust	METAR/mesonet observations
Large hail	Column graupel, updraft speed, ?	MESH
Tornado*	Updraft helicity	Post-processed MRMS rotation tracks
Lightning	Lightning flash algorithm	GLD360/NLDN
Visibility/Ceiling	Post-processed field in development	ASOS or future CIMSS technique
General Convection	Vertical motion, stability, reflectivity	MRMS reflectivity

HRRR-TLE: Project Timeline

Product Development Timeline

Engage National Center Testbeds

Organization/Experiment	Hazards	Platform	Timeline
WPC WWE	PQPF, Snowfall, Snow Rate	NAWIPS and web site	January 2016
NSSL/SPC EFP/EWP	Tornadoes, Hail, Wind	NAWIPS and AWIPSII	May 2016
WPC FFaIR	Refined PQPF and FF guidance	NAWIPS	June 2016
AWC Summer Experiment	Initial aviation hazards: ceiling, visibility, convection	NAWIPS	August 2016
WPC WWE	Refined winter hazards and PQPF	NAWIPS	January 2017
AWC Winter Experiment	Ceiling and visibility	NAWIPS	February 2017
NSSL/SPC EFP/EWP	Refined severe weather guidance	NAWIPS and AWPSII	May 2017
WPC FFaIR	Refined FF guidance	NAWIPS	July 2017
AWC Summer Experiment/OPG	Refined aviation hazards	NAWIPS and AWPSII	August 2017
Initiate NCO 'on-boarding"	All	IDP	Late 2017 or 2018

HRRRE Future Work

Refine ensemble data assimilation and forecasting

- Install radar reflectivity data assimilation
- Stochastic physics (parameter perturbation, tendencies for both DA and forecasting)
- Apply HRRR-TLE statistical post-processing
- Include lagged members?

Real-Time Status

Resume real-time HRRRE runs in Oct/Nov 2016 after ending 20 June 2016
HRRR-TLE runs continually available

Together (EMC, ESRL, NSSL, NCAR, …) work toward building a national real-time storm-scale ensemble system (and eventually a global storm-scale ensemble system)